COHERENT AND NONCOHERENT DETECTION IN DENSE ARRAYS: CAN WE IGNORE MUTUAL COUPLING?

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Motivation

New research lines in communications such as holographic MIMO propose to use arrays with a massive number of densely deployed antennas. However, most literature on classical and massive MIMO focuses on half-wavelength spaced arrays, where coupling may be neglected.

In this work, we explore the implications of mutual coupling in MIMO systems with closely spaced antennas. Our study focuses on the impact of coupling on symbol detection, both in single-user coherent and noncoherent systems.

Signal Model

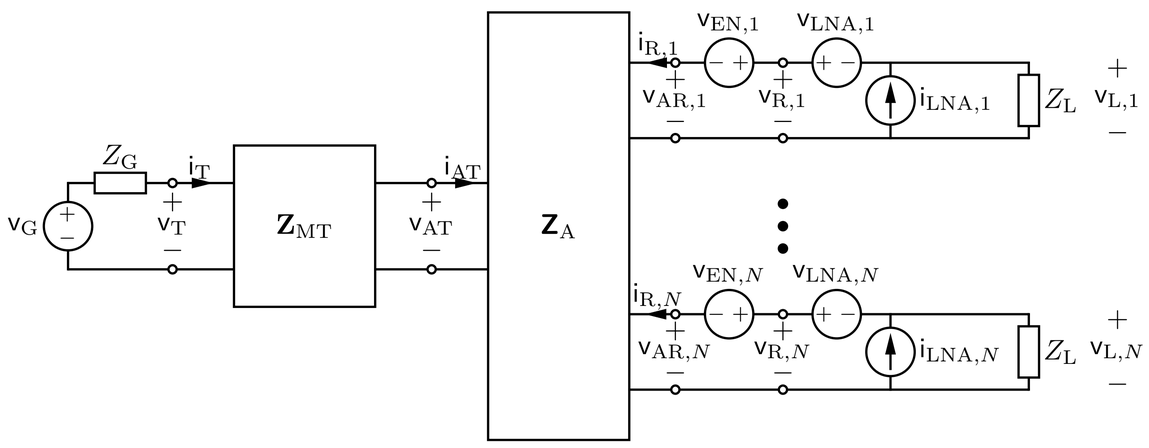

Figure 1. Circuit model of a SIMO communication system.

- ULA with N side-by-side dipole antennas separated $d = D/(N-1)$.
- NLoS propagation:
- M-PAM constellation $\mathcal{X} = \{0, x_2, \dots, x_M\}$.

The array response for the wave arriving from the scatterer $\mathbf{s}_i = (r_i, \theta_i)^{\mathrm{T}}$ is:

$$\mathbf{a}_i = \left(\frac{\mathrm{e}^{-\mathrm{j}k\|\mathbf{s}_i - \mathbf{u}_0\|}}{k\|\mathbf{s}_i - \mathbf{u}_0\|}, \dots, \frac{\mathrm{e}^{-\mathrm{j}k\|\mathbf{s}_i - \mathbf{u}_{N-1}\|}}{k\|\mathbf{s}_i - \mathbf{u}_{N-1}\|} \right)^{\mathrm{T}}, \tag{1}$$

with k the angular wavenumber and $\mathbf{u}_n = (nd, 0)^{\mathrm{T}}$ the nth antenna.

The received signal is:

$$\mathbf{y} = \mathbf{h}\mathsf{x} + \mathbf{z}, \quad \mathbf{h} \sim \mathcal{CN}(\mathbf{0}_N, \mathbf{R}_{\mathbf{h}}), \ \mathbf{z} \sim \mathcal{CN}(\mathbf{0}_N, \mathbf{R}_{\mathbf{z}}), \ \mathsf{x} \in \mathcal{X}. \tag{2}$$

Covariance matrices are modeled through the multiport communication theory framework as:

$$\mathbf{R}_{\mathbf{z}} = \mathbf{Q}(\mathbf{R}_{\mathrm{EN}} + \mathbf{U}_{\mathrm{LNA}})\mathbf{Q}^{\mathrm{H}} \tag{3}$$

$$\mathbf{R}_{\mathbf{h}} = \frac{1}{4R_{\mathrm{G}}\Re(Z_{\mathrm{A}})}\mathbf{Q}\mathbf{R}_{\mathrm{ART}}\mathbf{Q}^{\mathrm{H}}, \tag{4}$$

where

$$\mathbf{R}_{\mathrm{EN}} = 4k_{\mathrm{B}}T_{\mathrm{A}}B_{\mathrm{W}}\Re(\mathbf{Z}_{\mathrm{R}}),$$
$$\mathbf{U}_{\mathrm{LNA}} = \sigma_i^2(R_{\mathrm{N}}^2\mathbf{I}_N + \mathbf{Z}_{\mathrm{R}}\mathbf{Z}_{\mathrm{R}}^{\mathrm{H}} - 2R_{\mathrm{N}}\Re(\rho^*\mathbf{Z}_{\mathrm{R}})),$$
$$\mathbf{R}_{\mathrm{ART}} = \Re(Z_{\mathrm{A}})^2 \sum_{i=1}^{L} \beta_i \mathbf{a}_i\mathbf{a}_i^{\mathrm{H}}, \quad \beta_i \in \mathbb{R}$$

account for extrinsic noise, LNAs noise and inter-array coupling (*i.e.* propagation). $\mathbf{Q} = Z_{\mathrm{L}}(Z_{\mathrm{L}}\mathbf{I}_N + \mathbf{Z}_{\mathrm{R}})^{-1}$ is an auxiliary matrix that contains the intra-array coupling, $\mathbf{Z}_{\mathrm{R}}$, modeled as the impedances between half-wavelength dipoles.

Receiver Structure

Noncoherent detector: $\hat{x}_{\mathrm{NC}} = \arg\min_{x\in\mathcal{X}} \mathbf{y}^{\mathrm{H}}\mathbf{R}_{\mathbf{y}|x}^{-1}\mathbf{y} + \log|\mathbf{R}_{\mathbf{y}|x}|$.

- $\mathbf{R}_{\mathbf{y}|x} = |x|^2\mathbf{R}_{\mathbf{h}} + \mathbf{R}_{\mathbf{z}}$.
- $\widehat{\mathbf{R}}_{\mathbf{y}|x} = \gamma_1|x|^2\mathbf{R}_{\mathrm{ART}} + \gamma_2\mathbf{I}_N$.

Coherent detector: $\hat{x}_{\mathrm{C}} = \arg\min_{x\in\mathcal{X}} \left| \frac{\Re[\mathbf{h}^{\mathrm{H}}\mathbf{R}_{\mathbf{z}}^{-1}\mathbf{y}]}{\mathbf{h}^{\mathrm{H}}\mathbf{R}_{\mathbf{z}}^{-1}\mathbf{h}} - x \right|$.

- $\mathbf{h} = \sqrt{\frac{\Re(Z_{\mathrm{A}})}{4R_{\mathrm{G}}}}\mathbf{Q}\sum_{i=1}^{L}\alpha_i\mathbf{a}_i$.
- $\hat{\mathbf{h}} = \mathrm{j}\sqrt{\gamma_1}\,\Re(Z_{\mathrm{A}})\sum_{i=1}^{L}\alpha_i\mathbf{a}_i$, $\widehat{\mathbf{R}}_{\mathbf{z}} = \gamma_2\mathbf{I}_N$.

Numerical Results

Performance of the **coherent (C)** and one-shot **noncoherent (NC)** detectors is evaluated in three scenarios: a **matched (M)** detector with the correct signal model, a **mismatched (MM)** detector that ignores mutual coupling (*i.e.* $\mathbf{Z}_{\mathrm{R}} = Z_{\mathrm{A}}\mathbf{I}_N$), and a detector designed for an artificial **uncoupled (U)** scenario.

Parameter	Value	Parameter	Value
Carrier frequency	$f = 30\,\mathrm{GHz}$	Variance of the current noise source	$\sigma_i^2 = 2k_{\mathrm{B}}B_{\mathrm{W}}T_{\mathrm{A}}/R_{\mathrm{N}}$
Bandwidth	$B_{\mathrm{W}} = 20\,\mathrm{MHz}$	Antenna impedance	$Z_{\mathrm{A}} = 73 + \mathrm{j}42.5\,\Omega$
Amplifier and load impedance	$Z_{\mathrm{G}} = Z_{\mathrm{L}} = 186 - \mathrm{j}31.6\,\Omega$	Complex correlation coefficient	$\rho = 0.2730 + \mathrm{j}0.1793$
Noise temperature of antennas	$T_{\mathrm{A}} = 290\,\mathrm{K}$	LNA resistance	$R_{\mathrm{N}} = 5\,\Omega$

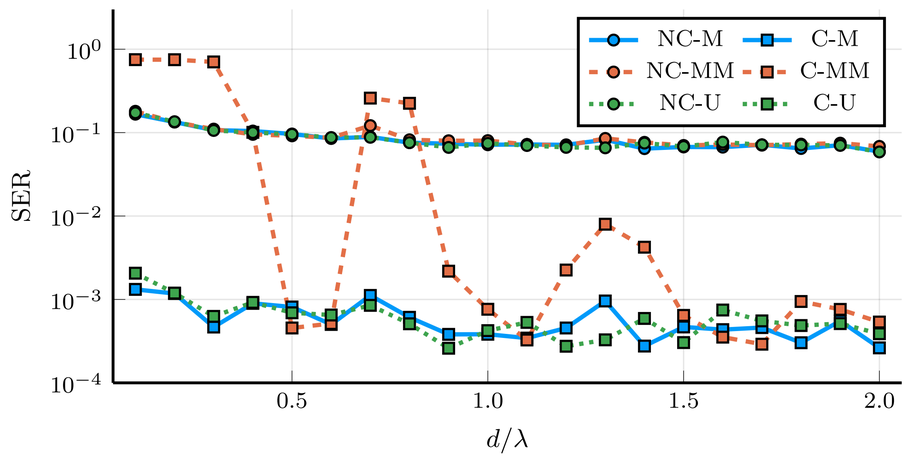

Figure 2. Error probability as a function of element separation for $N = 128$.

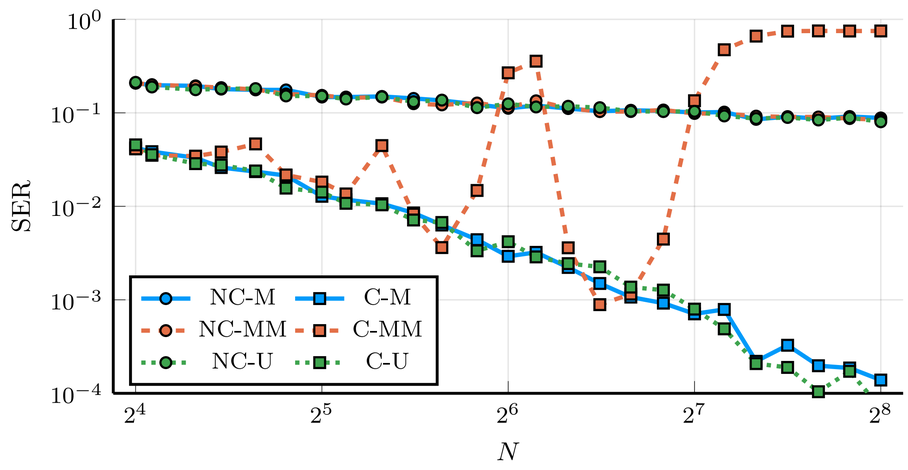

Figure 3. Error probability in terms of N for a fixed aperture $D = 0.5\,\mathrm{m}$.

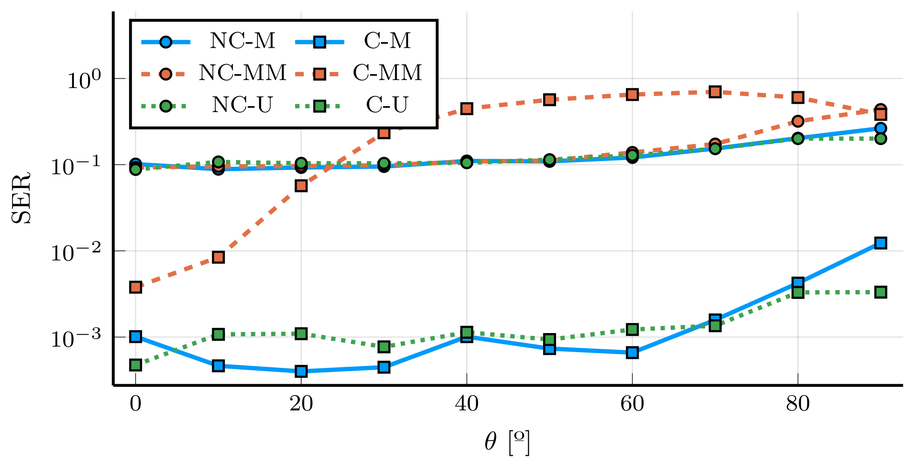

Figure 4. Error probability at azimuth angles from 0° to 90° with $D = 0.5\,\mathrm{m}$ and $N = 128$.

References

[1] A. Martí, L. Sanguinetti, J. Riba, and M. Lamarca, *Coherent and noncoherent detection in dense arrays: Can we ignore mutual coupling?* 2025. arXiv: 2506.19470 [eess.SP].

[2] A. A. D'Amico and L. Sanguinetti, "Holographic MIMO communications: What is the benefit of closely spaced antennas?" *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 13 826–13 840, 2024.

Acknowledgments

This work was (partially) funded by project MAYTE (PID2022-136512OB-C21) by MICIU/AEI/10.13039/501100011033 and ERDF/EU, grant 2021 SGR 01033 by Departament de Recerca i Universitats de la Generalitat de Catalunya and grant 2023 FI "Joan Oró" 00050 by Departament de Recerca i Universitats de la Generalitat de Catalunya and the ESF+. L. Sanguinetti was supported by the Italian Ministry of Education and Research (MUR) in the framework of the FoReLab Project and in part by the EU under the Italian NRRP of NextGenerationEU, partnership on "Telecommunications of the Future" (PE00000001 – Program "RESTART").

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